Application of the Surface Method for Vibration Analysis to CNC-Routers

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Abstract

In any woodworking machinery, vibrations cause a periodic change of the relative position between workpiece and tool. In milling and planing this can lead to a deficient surface quality, depending on the chosen process parameters and the machine's dynamic behavior. For modern machinery, the capability of performing high axis speeds and accelerations becomes of increasing importance. High axis accelerations lead to quasi-static deflections due to the mass moments of inertia. Depending on the dynamic compliance of the structure, these deflections lead to low frequency vibrations, which decay according to the modal damping constant. This paper describes a test to evaluate the dynamic behavior of machinery, especially routers, which is based on investigations of the machined workpiece. The surface method allows to determine in-process vibrations by investigation of a workpiece surface, machined with a specially prepared tool. Experimental results, showing the accuracy of the method when applied to routers, will be discussed. Valuable information about the dynamic behavior of the machine can be attained by examining a standardized workpiece, which was machined using standardized process parameters. This should lead to a new dynamic machining test that allows to compare the capabilities of machinery.

Introduction

The dynamic behavior of woodworking machines plays an important role for the quality of the produced workpieces /1/. Vibrations during machining generally result in a modified surface texture or in a dimensional error. For woodproducts, the irregular surface texture is the more significant problem. Especially after laquering or varnishing, the aesthetic impression of the surface is disturbed /2/.

Different models have been proposed to describe the milling process and the origination of the workpiece surface under consideration of the process kinematics as well as the effective machining forces /3-6/. These models were mainly developed for metalworking. They can also be used for woodworking, as long as machining forces and material constants are not taken into account. A simulation program that predicts the surface generation under the influence of in-process vibrations was introduced in /1/.

For any dynamic optimization of the milling process with the focus on an increased surface quality, one needs an exact knowledge about those vibration components, that cause the deficient surface quality /7/. The surface method for vibration analysis allows to gather the information about frequencies and amplitudes of in-process vibrations directly from the machined surface /8/. The applicability of the method to wooden surfaces was proven for the example of a moulder /9/.

This paper deals with the application of the method to routers, which are one of the most important machine groups in woodworking, because of their wide range of possible applications. Experimental investigations proved the accuracy of the method. Finally, a standardized test is proposed to evaluate the dynamic behavior of routers on the basis of a machined test workpiece.

Theoretical Background of the Surface Method

The superposition of the rotational cutting motion and the translational feed motion in peripheral milling leads to cyclodical grooves on the workpiece surface. Both, the groove width and the regular groove pattern are important factors for the surface quality. Especially after varnishing or staining, an irregular groove pattern is found unacceptable. The groove width depends on the feed per revolution, while irregularities of the groove pattern are either a result of vibrations during cutting or of unequal tooth radiuses /7/.

Every groove on the workpiece surface is cut during a time interval Δt. Assuming that the contact length within the groove approximately equals the feed length per tooth, geometrical considerations lead to the following equations:

$$\frac{r}{2 \cdot p} \approx \frac{f_z}{p \cdot D} \quad \text{and} \quad \frac{\Delta t}{t_z \cdot z} = \frac{r}{2 \cdot p} \ , \qquad (1), (2)$$

with φ representing the angle between the beginning and the end of the groove and t_z representing the time that passes between two successive tooth contacts. Resolving these equations leads to

$$\Delta t = \frac{f_z \cdot t_z \cdot z}{p \cdot D} = \frac{v_f}{v_c} \cdot t_z \qquad (3)$$

Providing that the ratio between v_f and v_c is very small, the creation time Δt for a groove is very short compared to the time t_z between successive tooth contacts (3). During this short time interval Δt, the relative position of workpiece and tool barely changes. As long as high-frequency vibrations are not taken into consideration, in-process vibrations therefore do not influence the shape of the grooves, but only their levels. High-frequency vibration components (> 5 times the rotational frequency of the tool) are generally of a small amplitude and therefore not relevant for the surface quality. Since only the levels of the grooves are affected by vibrations, all information about the instantaneous relative position of workpiece and tool can be taken from the level of the respective groove's base.

For an ideal cutting process, every cutting edge leaves exactly one groove per revolution. In that case, the information about the relative motion between workpiece and tool can be obtained by identifying the levels of the trough points of all grooves and determining the corresponding creation times t_N using the rotational frequency or the feed rate as the time basis. Unfortunately, in a normal cutting process not every cutting edge leaves one groove per revolution. Due to vibrations or unequal tooth radiuses, some cutting edges penetrate the material deeper than others. Because of this, some grooves may be removed from the surface partly or completely by the successive cutting edge. As a consequence, information about the relative position of workpiece and tool is missing and the time domain signal can not be composed.

To obtain the time domain signal, it must be ensured, that every cutting edge leaves at least one groove per revolution. This can be achieved by using a so-called coding tool. This is a specially prepared miller with some areas on the cutting edges ground back by a small amount. Only defined parts of the original cutting edge, the so-called coding teeth, remain unground and thus trace a path of slightly larger radius. The coding teeth are staggered in the axial direction of the tool. As a consequence, every coding tooth leaves its own trace of grooves on the workpiece surface, figure 1.

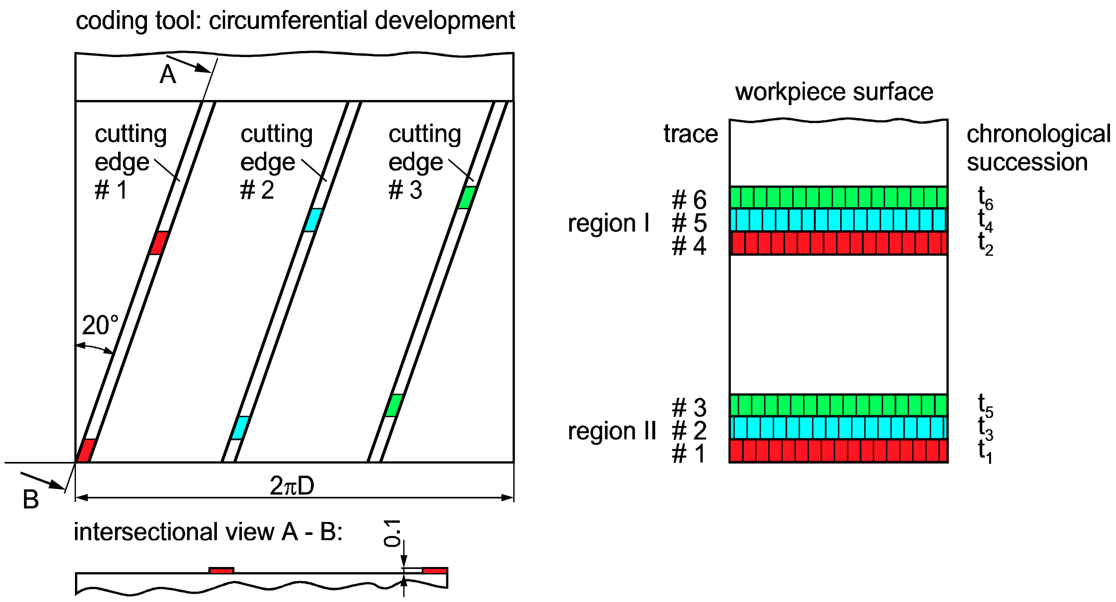


Figure 1: Coding tool and resulting workpiece surface

The amount by which the teeth are ground back depends on the dimensions of the tool as well as on the amplitude of expected vibrations. Grinding them back too far would mean that the coding teeth would do a disproportional large amount of the cutting and would wear out quickly. Furthermore, this can lead to torn grain which makes it difficult to find the trough points of the grooves accurately. For an end milling cutter with 16 mm in diameter, a recess of the cutting edges of 0,1 mm turned out to be an appropriate measure.

The coding tool shown in figure 1 is double coded. Every cutting edge carries two coding teeth. The coding teeth are arranged in a way, that the time intervals between the contacts of two successive coding teeth are all equal. Each cutting edge leaves two grooves per revolution, which were cut at two different creation times. The increased number of grooves cut per revolution means an increased number of points in the time domain signal of the relative movement between workpiece and tool.

Each trace on the workpiece surface originates from only one coding tooth. All these traces are scanned with a contact stylus profilometer. In a next step, the trough points of the grooves are determined. The identified trough points are then arranged according to the times at which the grooves were cut, figure 2. The order in which the points have to be composed depends on the arrangement of the coding teeth on the tools circumference.

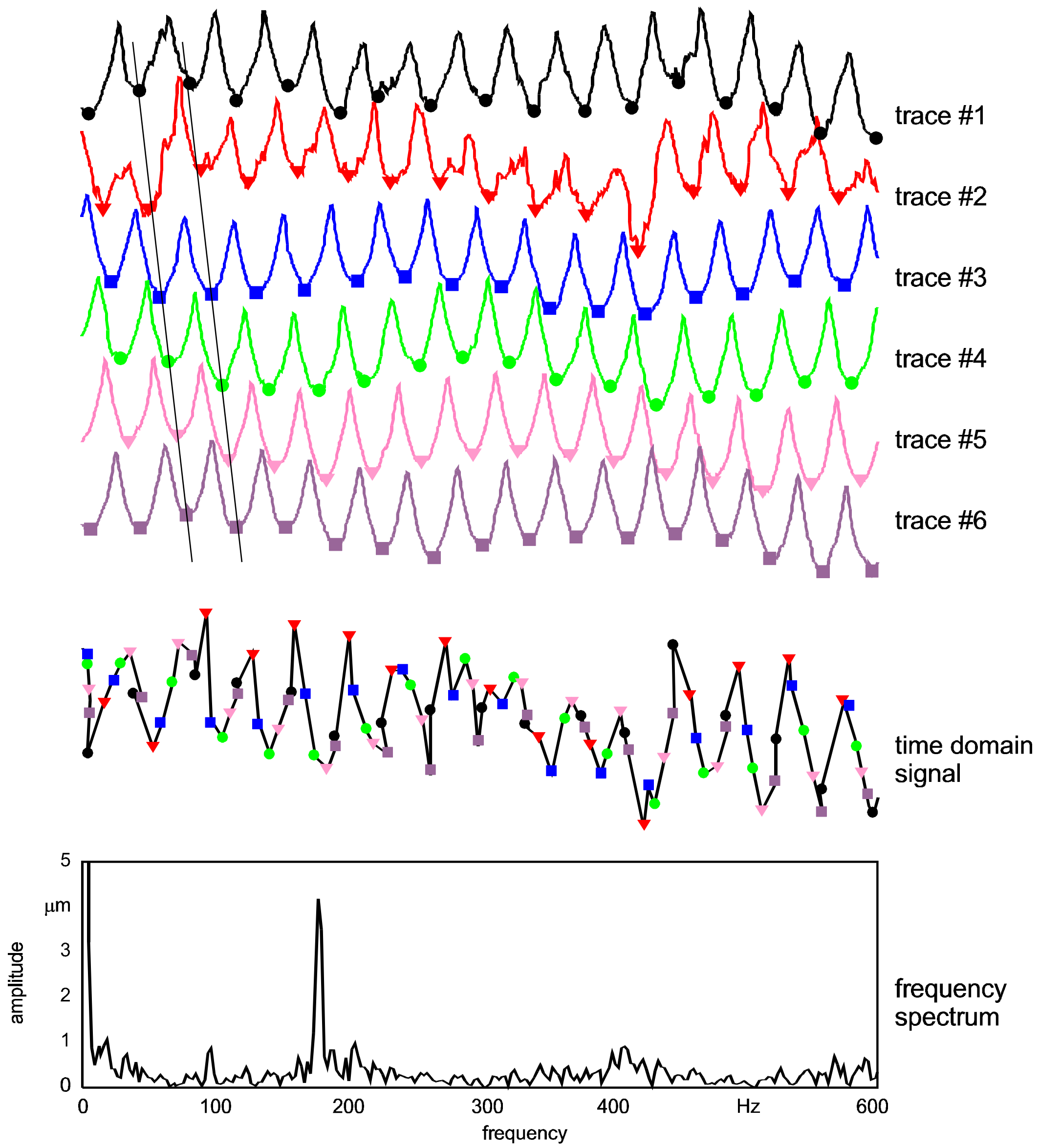


Figure 2: Time domain signal generated from the groove trough points and corresponding frequency spectrum

Once the time domain signal of the relative motion between workpiece and tool is composed, the corresponding frequency spectrum is obtained by performing a Fast Fourier Transform (FFT). An important requirement for the FFT is, that the time intervals between two successive points in the time domain signal are all equal. This is guaranteed by the arrangement of the coding teeth on the tool's circumference in combination with a constant feed rate per tooth.

If vibrations at the rotational frequency or its harmonics are superimposed to a milling process, the relative position between workpiece and tool is the same every time one certain coding tooth cuts a groove /2/. As a result, the traces on the workpiece surface are then on different levels. This offers the opportunity to filter the rotational frequency and it's harmonics out of the spectrum by equalizing the levels of the recorded traces. To do this, each trace's mean value is subtracted from each point of the measured profile. The reason for filtering out the unbalance and its harmonics is, that in most cases these vibration components are not responsible for the deficient surface quality, especially the irregular groove pattern. Nevertheless, they are dominating in the frequency spectrum because of their comparatively large amplitudes. Those vibration components, that are responsible for the deficient surface quality, are therefore easily overseen.

The limitations of the surface method depend on the tool’s geometry, it’s rotational frequency, the feed rate, and the traverse length of the profilometer as well as on the parameters of the imposed vibrations. According to Shannon’s theorem for the sampling of periodic signals, the sampling frequency f_{sample} must be at least twice as high as the maximum frequency to be identified f_{max} . With the sampling frequency, which depends on the tool’s rotational frequency and the number of coding teeth, this leads to

$$f_{\max} < \tfrac{1}{2} \cdot f_{sample} = \tfrac{1}{2} \cdot n \cdot z_c \ . \qquad (4)$$

The frequency resolution Δf equals f_{max} divided by the number of points in the time domain signal. This number depends on the feed rate per revolution f, the number of coding teeth z_c, and the traverse length l of the profilometer:

$$\Delta f = \frac{2 \cdot f_{\max}}{N} = \frac{2 \cdot f_{\max} \cdot f}{l \cdot z_c} = \frac{v_f}{l} \ . \qquad (5)$$

The amplitude limit A_{max} depends on the tool’s diameter D, the feed per revolution f and on the ratio η between the frequency of vibration and the rotational frequency of the tool /9/:

$$A_{\max} = \frac{D}{4 \cdot \sqrt{\sin^2(hp)}} \cdot \left(1 - \sqrt{1 - \frac{4 \cdot f^2}{D^2}}\right) \ ; \quad h = \frac{w_{vibr}}{w_{tool}} \ . \qquad (6)$$

Figure 3 shows the surface profile in one single trace. The upper part of the picture shows the generation of the surface profile when the amplitude of the imposed vibration is below the amplitude limit. One certain coding tooth (shaded in figure 3) leaves exactly one groove per revolution. Due to vibrations, some grooves are comparatively deep, whilst others are short and shallow. In the lower part of figure 3, the amplitude limit is just reached. The short grooves are completely removed from the surface. The examined coding tooth leaves one groove only every second revolution.

Figure 3 shows the most critical case when the frequency of the imposed vibration equals half the rotational frequency of the tool (η = 0.5) and the phase shift is 0°. Frequency ratios η ≠€0.5 + i; i = 1, 2, ... result in larger amplitude limits. The poles of equation (6) lie at the rotational frequency and its harmonics. In those cases all coding teeth contact the surface once per revolution independently from the amplitude. Only the levels of the traces are affected by these vibrations.

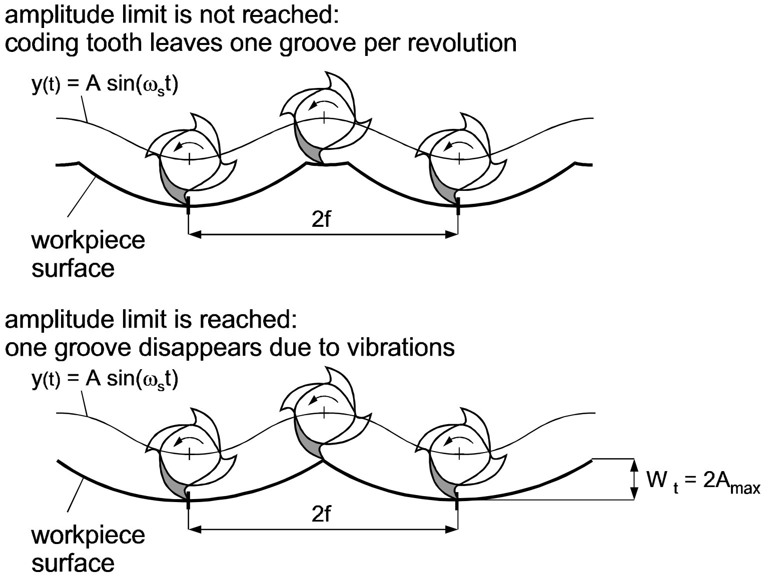


Figure 3: Amplitude limit for the surface method for vibration analysis

For wood surfaces, some problems may occur when scanning the wooden surfaces with a contact stylus profilometer. Fibers and pores may disturb the surface profiles, so that the grooves are not to be seen. As a consequence, the levels of the trough points can not be determined accurately, if at all. The influence of fibers and pores on the measured profile can be reduced with an appropriate scanning technique /9,10/. Firstly, a wedge-shaped stylus tip, used instead of a spherical one, does not register the small pores, because it glides over them. Secondly, an increased contact force avoids that small fibers cause a deflection of the stylus. Both measures, the wedge-shaped stylus and the increased contact force, act like a mechanical filter that suppresses the influence of the material’s roughness.

Despite the application of that mechanical filter, especially in the bottom regions of the grooves the profiles are often not completely smooth. This complicates the identification of the trough points. Numerical methods are helpful to determine the accurate positions of the trough points. Each groove is approximated by the segment of the circle with the tool’s diameter, figure 4. The center point of this circle is then shifted in iterative steps until the curvature fits the actual groove of the measured profile best by means of a minimum RMS error. The trough point of the groove is then assumed to lie directly underneath this center point of the circle.

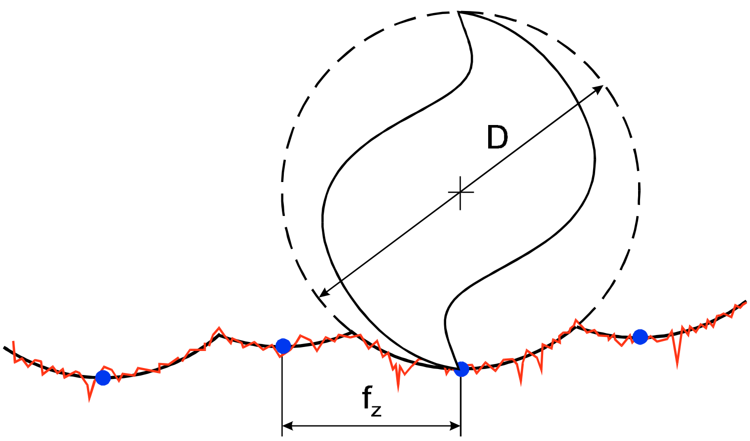


Figure 4: Approximation of the measured groove by a circle segment

Application to CNC-Routers

Because of their wide range of possible applications, routers are one of the most important machine groups in woodworking. The surface method for vibration analysis proved to work fine for moulders /9/. The experiments described in the following demonstrate the accuracy of the method when applied to routers. The photograph below shows the coding tool with the raised coding teeth distributed on the circumference, figure 5.

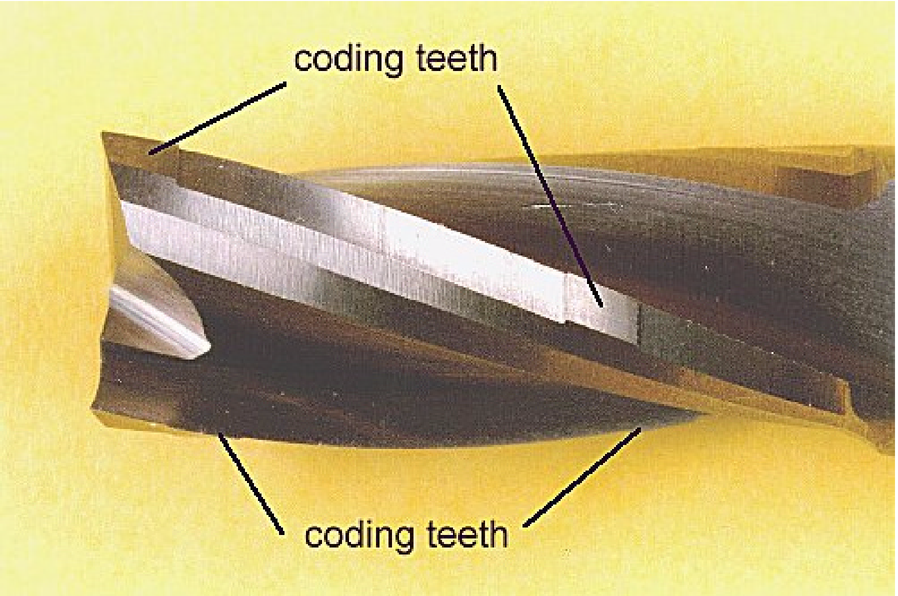


Figure 5: Coding tool with coding teeth; D = 16 mm, $z = 3$, $z_c = 6$

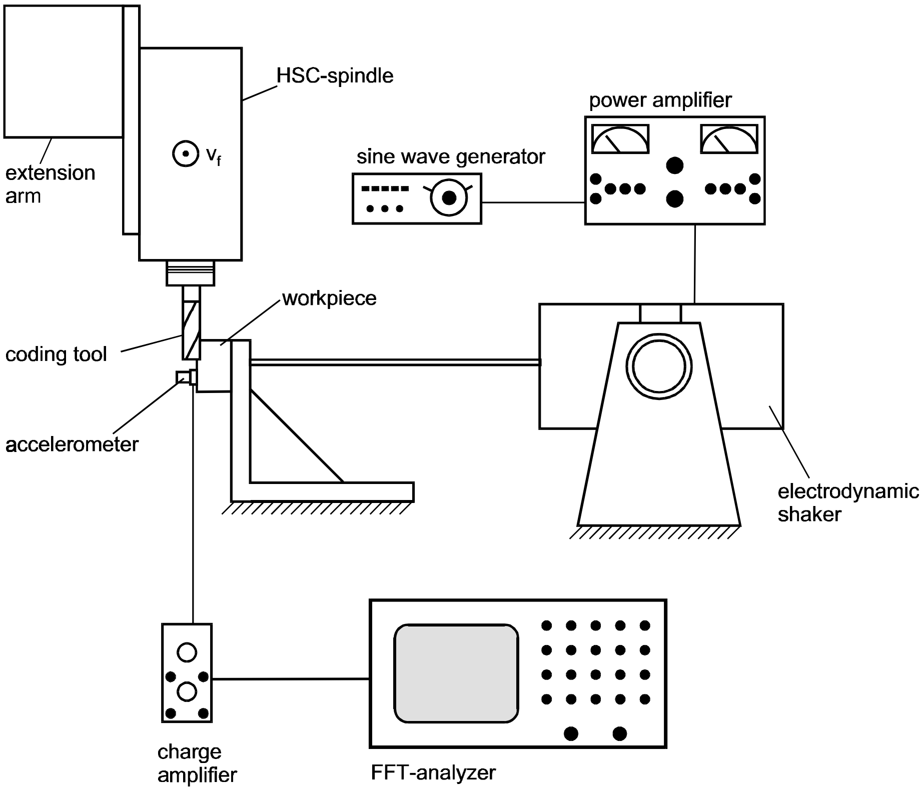


Figure 6: Experimental setup to prove the frequency and amplitude accuracy of the surface method

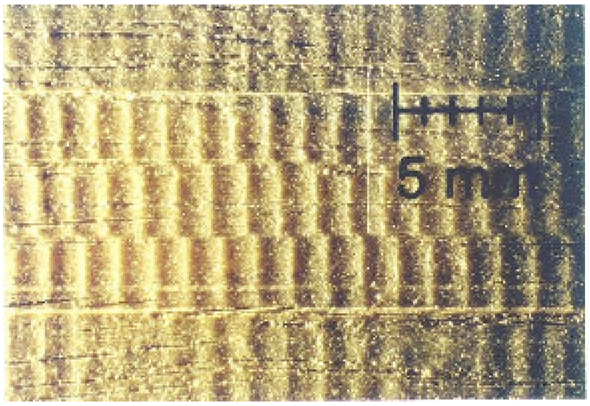
The experimental setup is shown in figure 6. An electrodynamic shaker a was used to excite the workpiece holding device with a vibration of known frequency and amplitude. The vibration was controlled with a FFT-analyzer and an accelerometer, which was positioned on the workpiece surface. The workpiece material was beech (*fagus sylvatica*) in the dimensions 50x65x200 mm. Both, amplitude and frequency of the introduced vibration were adjusted at standstill and remained unchanged during subsequent machining with the coding tool. With the accelerometer positioned below the machined area, the vibration parameters could be monitored during operation. It turned out, that the assumption of unchanged frequency and amplitude of the introduced at standstill and during machining is correct.
Two series of experiments with superimposed vibrations had been carried out to prove the amplitude and frequency accuracy of the surface method. The machining parameters were the same in both series: $n = 12300\ min^{-1}$, $v_f = 15$ m/min, $a_e = 1$ mm, $a_p = 35$ mm, D =16 mm, z = 3, $z_c = 6$.
After machining, the surface was scanned with the profilometer. Subsequently, the generated surface profiles were analyzed with a newly developed identification software, called WinIdent. This software computes the trough points of all grooves and composes the time domain signal of the relative motion between workpiece and tool. A FFT-algorithm is also implemented to transform this time domain signal into the frequency domain. The graphical user interface makes the software easy to learn and helps to avoid mistakes.
In the first series of experiments, the amplitude of the introduced vibration remained constant (A = 4.5 µm), while the frequency was increased step by step to 30 Hz, 60 Hz, 100 Hz, 150 Hz, 200 Hz, 250 Hz, 300 Hz, and 350 Hz. The results obtained from the vibration analysis using the surface method are shown in table 1. Within the frequency resolution according to equation (5), the frequencies identified with the surface method are the same as those introduced.

Frequency variation experiments: A = 4.5 mm (constant)								
Introduced Vibration [Hz]	30	60	100	150	200	250	300	350
Identified Vibration [Hz]	31.1	59.8	100.5	150.7	198.5	248.8	299.1	349.3

Table 1: Frequency accuracy of the surface method

To achieve these accurate results, it is essential to specify the process parameters (revolutions per minute, feed rate) exactly, because the software uses this information to compute the time basis of the time domain signal. Since the frequency information is used to identify a vibration component and to find the corresponding mode of vibration from modal analysis results, the frequency accuracy of the method is of great importance.

In a second series of experiments, the frequency of the introduced vibration remained constant (f = 180 Hz), while the amplitude was increased for every new workpiece. It was adjusted to 2.60 µm, 3.45 µm, 4.35 µm, 5.20 µm, 6.10 µm, 7.00 µm, 7.65 µm, 8.75 µm, and 10.50 µm. As an example, figure 7 shows the result for a vibration of 180 Hz with an amplitude of 7.0 µm. The photograph in the left part shows three traces on the surface. The appropriate frequency spectrum as the result of the surface analysis is shown on the right. The complete results of the amplitude variation experiments can be found in table 2.



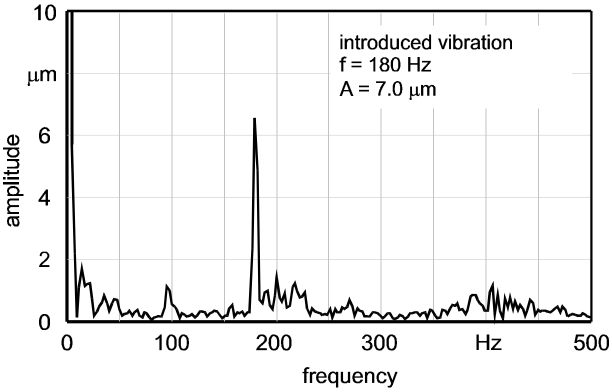


Figure 7: Amplitude accuracy of the surface method

Amplitude variation experiments: f = 180 Hz (constant)									
Introduced Vibration [µm]	2,60	3,45	4,35	5,2	6,1	7,0	7,65	8,75	10,5
Identified Vibration [µm]	2,5	3,5	4,2	4,5	5,7	6,5	7,5	8,4	10,3

Table 2: Amplitude accuracy of the surface method

In the photograph, three traces of coding teeth are clearly visible. In the regions above and below these traces, all cutting edges traced a path of the same radius. Without any relative movement between workpiece and tool, every cutting edge would have left exactly one groove per revolution. These grooves would then have a much shorter length than those in the coded regions. But as it can be seen in the photo, this is not the case. The average groove length is the same as within the coded traces and corresponds to the feed rate per revolution. The reason for this are vibrations at rotational frequency (due to a slight unbalance), which lead to a so-called „one-knife-finish“. Only one cutting edge forms the surface. Although the unbalance vibrations lead to a one-knife-finish in the uncoded regions of the workpiece surface, the spectrum shows no peak at the rotational frequency (f_{Rot} = 204 Hz), figure 7. The unbalance vibrations have been filtered out of the spectrum by equalizing the mean levels of the coded traces. Since the unbalance vibrations only affect the levels of these, they now can not influence the analysis result.

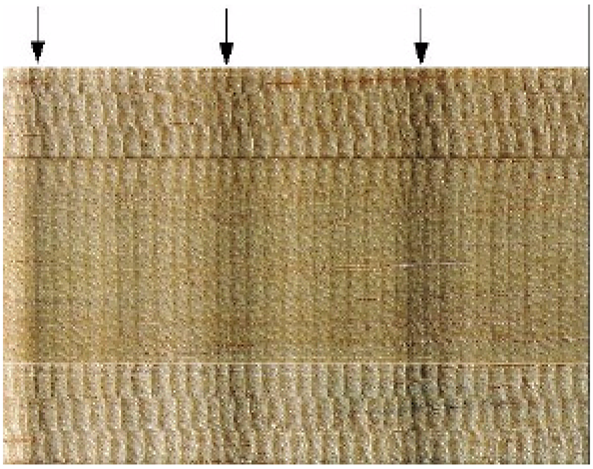
As the results in table 2 show, the surface method is well suited for a correct identification of the amplitude of relative vibrations between workpiece and tool. The maximum difference between the amplitude of the introduced vibration and that of the identified one is 0.7 µm. That means, that an evaluation of a certain vibration component’s influence on the surface quality can be done by comparing the identified amplitudes. However, it has to be taken into account, that a vibration’s influence on the surface quality does not exclusively depend on its amplitude. Simulations as well as experimental results show, that the frequency ratio between the superimposed vibration and the rotational frequency is of great evidence for the regularity of the surface pattern /2, 11/.

Machining Tests

The experiments with artificially generated vibrations proved the accuracy of the surface method when applied to routers. The surface method therefore recommends itself as a tool to describe and evaluate the dynamic behavior of the machine tool under machining conditions. For modern machining centers, the capability of performing high axis speeds and accelerations becomes of increasing importance. Problematic in this context are deformations of the machine structure due to the acting inertial forces. These deformations do not only lead to static deflections at the tool center point, but do also initiate vibrations at the structure’s lower natural frequencies. These vibrations decay according to the modal damping coefficient and usually lead to a deficient surface quality.

The use of the surface method in a standardized test allows to evaluate the machine’s dynamic behavior under realistic machining conditions. The results of this test may help to compare different machines regarding the dynamic stiffness and the attainable surface quality.

For the test proposed in the following, no vibrations from outside of the machine are introduced. The high accelerations that occur, when sharp corners are driven at high velocities, lead to deformations of the structure due to the acting inertial forces. These deformations result in relative vibrations between workpiece and tool. A square test workpiece of 150x150 mm was machined with a comparatively high feed rate. The sudden changes of direction in the corners of the workpiece initiate vibrations perpendicular to the actually machined surface, which can be identified with the surface method. Modern CNC offer a so-called look-ahead function, which makes the machine decelerate slowly prior to the corner. For the test, the look-ahead function needs to be disabled. The test workpiece was aligned in the machine’s main axes, so that the vibrations parallel to the x- and y-axis could be investigated. Because of its great roughness, end-grain wood is not suitable for a surface analysis with the profilometer. It is therefore of great importance, that the orientation of the test workpiece's end grain is upwards (in z-direction). The chosen machining parameters were the following: $n = 12300\ min^{-1}$, $v_f = 15$ m/min, $a_e = 1$ mm, $a_p = 35$ mm, $D = 16$ mm, $z = 3$, $z_c = 6$.



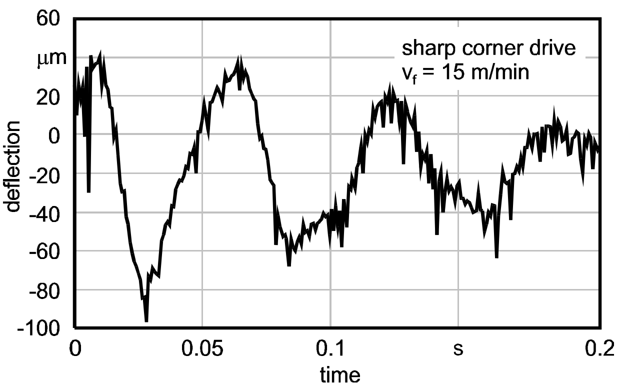


Figure 8: Machined surface: sharp corner driven with look-ahead function disabled and corresponding time domain signal

Figure 8 shows a photograph of the machined surface right behind the workpiece corner. Waves of a comparatively long wave length (≈€12 ·€f = 14.7 mm) superimposed to the groove pattern are clearly visible. These waves result from low frequency vibrations perpendicular to the surface. The time domain signal obtained from the surface analysis with the decaying vibration is shown on the right side of figure 8.

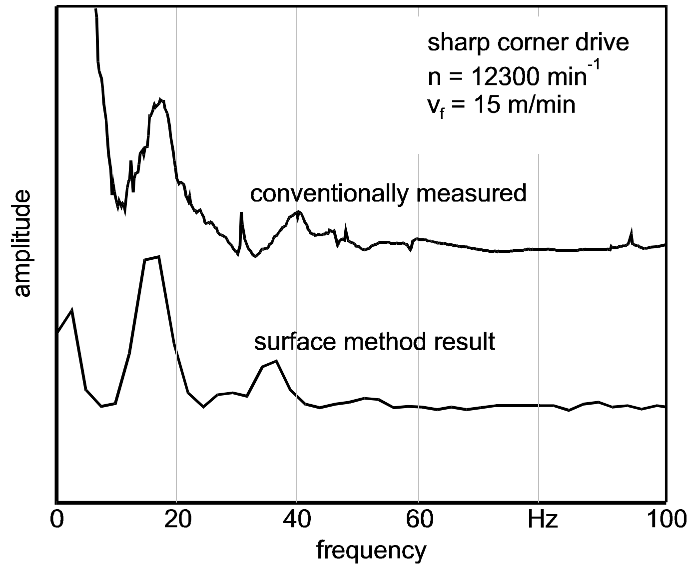


Figure 9:
Frequency spectrum obtained from the surface analysis compared to the frequency spectrum measured with conventional methods

Figure 9 compares the frequency spectrum obtained from the surface analysis to a spectrum, which was measured with an accelerometer at standstill. The amplitude axes of both spectra are not scaled, because the amplitude depends on the intensity of the respective excitation. Of course, the frequency resolution of the conventionally measured spectrum is better than that of the surface analysis result. But nevertheless, the similarity of both spectra is obvious. Both spectra show peaks at 18 Hz and 38 - 40 Hz. The peak at 18 Hz corresponds to the wave length, which could already be identified at first sight from the machined surface.
The described test represents a quick and easy way to get valuable information on the machine’s dynamic behavior. Different machines can be compared by machining identical workpieces with the same process parameters. One must also pay attention to comparable positions within the machine’s working area, since, depending on the design, the dynamic stiffness of a machine may be heavily influenced by the actual position of the spindle within the working area. For each machine, a "characteristic“ frequency spectrum is obtained, which allows a quick classification by means of the dominating frequencies and the corresponding amplitude values.

Conclusion

Generally, the surface method for vibration analysis offers three basic advantages in comparison to conventional measurements. Firstly, it allows to measure the relative movement between workpiece and tool under machining conditions and directly in the cutting point. Secondly, it is simple and quick. If the exact rotational frequency of the tool is known (to have an accurate time basis), no additional measuring equipment is needed at the machine. The time required for machining a test workpiece is comparatively short. While the actual surface analysis is done, the machine can already be used for normal production. Thirdly, the surface method allows an analysis from a distance. There's no need for an engineer to be present, when the test workpiece is machined. Only the machined workpiece and the chosen process parameters are required for a vibration analysis.

The experiments demonstrate the applicability of the surface method for vibration analysis to routers and modern machining centers. The results obtained with the surface method turned out to be very accurate, both in terms of amplitude and frequency. The surface analysis with a contact stylus profilometer worked well, if an appropriate scanning technique was applied.

The proposed test offers a good opportunity to quickly characterize the machine's dynamic behavior under machining conditions. If the process parameters, the workpiece dimensions, and the relative position of the workpiece within the machine's working area are the same, the frequency and the amplitude information obtained by this machining test may be helpful to compare different machines. The frequency spectra obtained with the described machining test correspond to those achieved from measurements at standstill with conventional measuring techniques.

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